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13. ABSTRACT ***(Maximum 200 words)***

During the interim period of this bridging contract, we have continued to work on the development of high-power cw diode-laser-array-pumped solid-state lasers. Towards that end, we have built lower power lasers in order to test individual components needed for the high-power laser; specifically we have built a 1 watt ring laser and a 5 watt slab laser. The 1 watt laser was used to study the injection locking process while assembling all the necessary electronics. We have demonstrated that it is possible to injection lock a diode-pumped laser using a single piezo-mounted mirror due to the lower intrinsic laser noise compared to an arc-lamp-pumped system. This allows us to optimize the injection locking servo loop and build a more stable locking system. The 5 watt laser was used as a test bed to find a practical way to mount the slab laser while minimizing the losses that occur at the total internal reflection (TIR) points in the slab. After trying many different means of protecting the TIR surfaces, we found that a new product from DuPont, Teflon AF 1600, has all the properties needed to provide a low loss protective coating. Using this material, the laser had a cavity loss of below 2%, which allowed for efficient operation of the laser in a side-pumped design. This laser produced 5 watts of output power with a slope efficiency near 20%.

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High-Power CW Diode-Laser-Array-Pumped Solid-State Lasers and Efficient Nonlinear Optical Frequency Conversion

Final Report
for the period
15 August 1993 to 15 December 1993

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High-Power CW Diode-Laser-Array-Pumped Solid-State Lasers
and
Efficient Nonlinear Optical Frequency Conversion

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Abstract

During the interim period of this bridging contract, we have continued to work on the development of high-power cw diode-laser-array-pumped solid-state lasers. Towards that end, we have built lower power lasers in order to test individual components needed for the high-power laser; specifically we have built a 1 watt ring laser and a 5 watt slab laser. The 1 watt laser was used to study the injection locking process while assembling all the necessary electronics. We have demonstrated that it is possible to injection lock a diode-pumped laser using a single piezo-mounted mirror due to the lower intrinsic laser noise compared to an arc-lamp-pumped system. This allows us to optimize the injection locking servo loop and build a more stable locking system. The 5 watt laser was used as a test bed to find a practical way to mount the slab laser while minimizing the losses that occur at the total internal reflection (TIR) points in the slab. After trying many different means of protecting the TIR surfaces, we found that a new product from DuPont, Teflon AF 1600, has all the properties needed to provide a low loss protective coating. Using this material, the laser had a cavity loss of below 2%, which allowed for efficient operation of the laser in a side-pumped design. This laser produced 5 watts of output power with a slope efficiency near 20%.

I. Research Results

In order to perform the desired nonlinear frequency conversion of the high-power, diode-pumped, solid-state laser to both the visible and mid-IR regions, it is necessary to obtain stable, single-frequency operation of the laser. This is necessary to couple the laser output into a resonant cavity, which allows for efficient nonlinear conversion. In order to obtain the frequency control of the laser, we will injection lock the high power laser to a frequency-stable, low-power master laser. Injection locking allows us to obtain stable, single-frequency operation without introducing intracavity optics such as an optical diode or an etalon which increase the cavity losses and decrease efficiency. In an attempt to study the intricacies of injection locking we built a low power laser, the 1 watt ring laser. This allowed us to build and test the servo electronics and associated RF components in a simpler system than the high power laser. These components will be used in the high power laser.

Once the low power laser was built we could examine the servo requirements to injection lock a diode-pumped laser system. Previously in our research group we have injection locked an arc-lamp-pumped system based on a water-cooled Antares head. In this system acoustic noise is so severe that both a fast and a slow piezo-mounted mirror are required for injection locking, and it is difficult to optimize the servo loop since both piezos and their respective servos must be operating at all times just to maintain lock. We have demonstrated that a diode-pumped system has lower intrinsic noise and can be injection locked using a single piezo-mounted mirror with a moderate bandwidth of 35 kHz. This allows for a detailed optimization of the servo loop and hence a more robust injection locked system. The 1 watt ring laser served as a test-bed for experimenting with piezo-mounted mirror systems and the servo electronics.

The success of the high power laser relies on the use of a slab laser geometry to overcome thermal problems such as thermal lensing and stress induced birefringence. In a rod laser design, uniform pumping of the cylindrical rod creates a radially dependent temperature gradient. This temperature gradient creates a thermal lens and modifies the radial and tangential index of refraction to create stress induced birefringence. If a polarizing element is placed in the cavity to create a polarized output, this birefringence creates loss and reduces the efficiency of the laser. In order to avoid these effects, we have chosen to use a zig-zag slab geometry. In this design, the beam enters a rectangular gain medium at Brewster's angle and propagates through the slab, using total internal reflection, in a zig-zag pattern between the two large surfaces of the slab. The slab is uniformly

pumped and cooled through the same surfaces to create a one-dimensional temperature profile. Since the beam propagates in a zig-zag pattern across this temperature gradient, the thermal effects are averaged away, and there is no thermal lensing or stress induced birefringence to first order in a uniform slab.

Since the total internal reflection (TIR) surfaces must be cooled in a slab laser, some mechanism must be used to preserve the TIR points from any coolant effects. A thick SiO_2 coating has been used in the past in conjunction with a water coolant. However, water cooling at the surface can create noise and it is difficult and costly to obtain the SiO_2 coating. We have used conduction cooling through a MgF_2 spacer in an attempt to minimize the noise introduced by the cooling system. This requires a coating on the slab that can absorb the stress created when the slab expands due to the thermal load. In addition, the coating must have a refractive index low enough to preserve the TIR reflection and be transparent at the pump wavelength. The coating must also be applied to the slab surface without introducing any microscopic gaps which create scatter at the laser wavelength due to a refractive index difference. We used a preliminary slab head design to test many different compounds and application techniques. These included a polyacrylate in an aerosol spray, a polyethylene film, a polyimide film adhesive, a fluorocarbon film and solution as well as a few other materials and application processes. We found that a new

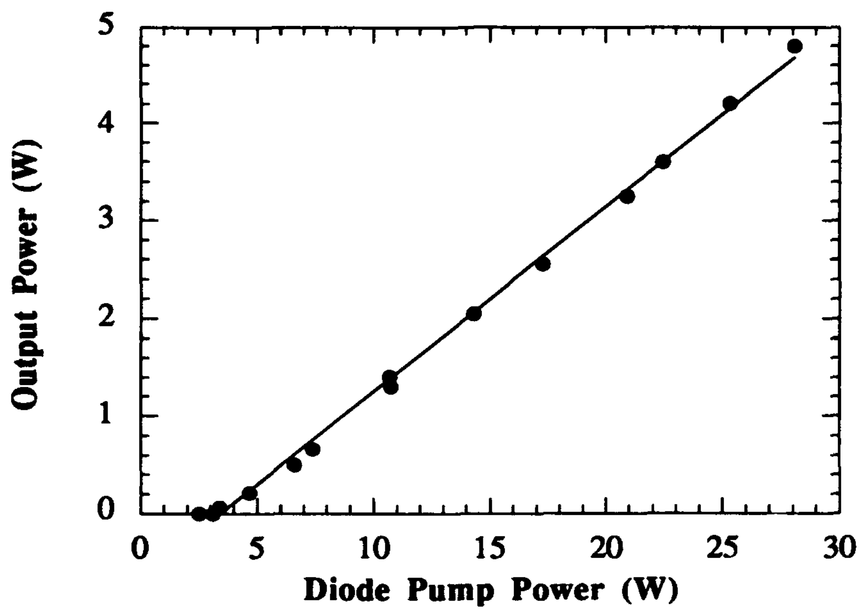

Figure 1. Diagram showing the output power at 1.06 μm vs. diode pump power. The slope efficiency was 19% with a threshold of 3.4 W.

product from DuPont, Teflon AF 1600, had the necessary properties for our application. We dissolved this material in a perfluorinated solvent and applied the material from solution. Using this method, the measured cavity losses were below 2%. By minimizing the cavity losses, the laser operated very efficiently for a side-pumped design. Using six fiber-coupled diode lasers as a pump source, we obtained 5 watts of output power at a pump power of 28 watts. Figure 1 shows the input-output curve for this laser.

The 5 watt laser has served as a useful test bed to experiment with the different schemes to protect the TIR surface while also cooling through the same surface. We have found a material which should allow efficient operation of the high-power laser by minimizing the cavity losses introduced at the TIR surface. In addition to developing this laser design, we have tested different pump geometries and verified the gain calculations critical to the design of the high power laser. This knowledge allowed us to intelligently modify the dimensions of the Nd:YAG slab medium to obtain high gain while avoiding stress fracture. We feel confident that the high power laser will operate as designed using the knowledge gained from these lower power lasers.

II. Scientific Personnel Supported by this Contract

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Tony Alfrey	Staff Scientist	Ginzton Laboratory

Students

Robert Shine

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III. List of Publication Supported by Contract DAAL03-93-0415

1. R. J. Shine Jr., A. J. Alfrey and R. L. Byer, "A 5-Watt 1.06-μm and a 1-Watt 1.32-μm, cw, TEM_{00} mode, Diode-Laser-Pumped, Nd:YAG Slab Laser," to be presented at the Advanced Solid State Laser Topical Meeting, February 1994, Salt Lake City, Utah.
   (A summary of this paper that will appear in the meeting proceedings is attached as an appendix to this report.)

Submitted to
1994 Advanced Solid State Lasers

A cw, TEM_{00} Mode, Diode-Laser-Pumped, Nd:YAG mini-Slab Laser

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One of the goals of our laser development program is to design and build a laser that meets the specifications for the Laser Interferometer Gravity-Wave Observatory (LIGO) program.[1] The LIGO requirements include single-frequency, polarized, fundamental-mode output at high power (≈100 watts) in continuous-wave operation. In our effort to demonstrate such a laser, we have begun by building lasers in the 5 to 10 watt range to test design ideas before implementing them in the more complicated and expensive high power laser. In this paper we discuss the design and operation of a Nd:YAG, zig-zag slab laser pumped with 28 watts of diode-laser power. A novel feature of this laser is a low loss, low cost Teflon® AF polymer protective coating applied to the total internal reflection (TIR) surfaces of the slab laser material.[2] This coating keeps the round-trip cavity losses low, allowing the laser to operate efficiently even with side-pumping. We have obtained 5 watts of output power at 1.06 μm in a TEM_{00} mode. The threshold was 3.4 watts and the slope efficiency was 19% with a 4% output coupler. In addition, the low cavity losses allow the laser to operate on the lower gain line at 1.32 μm, although the efficiency suffers. We have obtained output powers up to 1.1 watt at 1.32 μm, again in a TEM_{00} mode.

Many of the laser design choices are dictated by the application. We chose to fiber-couple the diode-laser pump sources to improve the system reliability. However, fiber-coupling reduces the brightness of the pump source and requires a side-pumped design. Our pump sources are Spectra Diode Labs SDL-3490-P5 diode lasers with 0.4 N.A, 400 μm core fibers.[3] We also chose to use a Brewster angle, zig-zag slab design over a rod for its greater thermal handling capabilities. In a true uniformly pumped zig-zag slab, the rectilinear geometry minimizes depolarization loss while the zig-zag optical path averages the thermal gradient to reduce thermal lensing.[4] In the past, most slab lasers were operated pulsed with a multi-transverse mode structure. The transverse mode structure filled the slab volume well and pulsed operation created high peak gains for efficient operation. In order to improve beam quality, unstable resonators can be used.[5] At high cw powers and in pulsed systems the gain is high enough to run an unstable resonator with a large mode to fill a large aspect ratio slab. At lower cw powers, between 3 and 20 watts, the gain is not high enough to run an unstable resonator effectively, so we could not operate a true zig-zag slab laser with uniform pumping. Instead, we chose to focus the pump power onto a narrow stripe along the slab. We achieved roughly 1:1 focusing of the pump fibers using two spherical f/1 lenses. This allowed us to run a stable cavity mode and thus to efficiently extract the pump power in a TEM_{00} mode. The slab was cooled through the large pumped surfaces, just as in a true zig-zag slab laser. However, in the side-pumped line design, there will be a cylindrical thermal lens and possibly some thermal aberrations in the non-zig-zag plane. The slab thickness was chosen to be roughly half an absorption depth to reduce the thermal gradient while absorbing a reasonable amount of the pump. The residual transmitted pump power was retroreflected using an f/1 mirror to refocus the pump for a second pass through the slab.

As mentioned, we built this 5 watt laser before building the high power diode-laser-pumped slab laser in order to test design ideas. Specifically, we investigated ideas for mounting and cooling the slab. We decided not to use direct water cooling at the slab surface for a few reasons although mostly because it is difficult to seal the Brewster-angle zig-zag slab laser with O-rings while not disturbing the TIR bounce at the surface, especially in the miniature slab laser we have built. Instead, we chose to directly conduction cool the slab through MgF_2 windows. Water flows behind this window to remove the heat, but does not interact with the slab TIR surface. MgF_2 is readily available, optically clear at the pump wavelength, easily polished, has a low refractive index of 1.37, a relatively high thermal conductivity of 21 $W\ m^{-1}\ K^{-1}$ and is cheap.[6] The low refractive index is not necessary to preserve the TIR bounce in the slab since we applied a protective coating to the slab surface, but it does reduce Fresnel reflections of the pump light. In the future the windows could be AR coated to avoid reflection of the pump.

To preserve the TIR reflection in the zig-zag slab, we designed a simple, low cost coating. A hard SiO_2 coating a few microns thick has been used in the past for this purpose[7] but instead we used a Teflon® AF polymer recently developed by DuPont. The Teflon® AF polymer has all the advantages of Teflon® but is optically clear and is soluble in perfluorinated solvents.[2] To create the protective coating, we used a solution of the Teflon® AF polymer in a Fluorinert® solvent made by 3M.[8] The solution was applied to the TIR faces of the slab and the solvent was allowed to evaporate. This Teflon® AF coating is quite durable, we have noticed no degradation in laser power during use. In addition the coating can be removed simply by redissolving the Teflon® AF in the Fluorinert® solvent. The protective coating works well, giving a round-trip cavity loss between 1 and 1.7% as measured using the Findlay-Clay method.[9] This cavity loss includes TIR loss for 10 bounces in the slab, bulk scatter and absorption loss for a beam path of 2.7 cm in the gain medium, residual depolarization loss, mirror scatter and clipping loss. A similar laser using Nd:YAG from the same source but without any protective coating has a measured cavity loss of 5.6%.[10] It is the low loss design of this laser which allows it to operate efficiently at 1.06 μm even in a side-pumped geometry. The low loss also allows the laser to operate on the lower gain 1.32 μm line, although with reduced efficiency due to the lower quantum defect and a lower output coupler value.

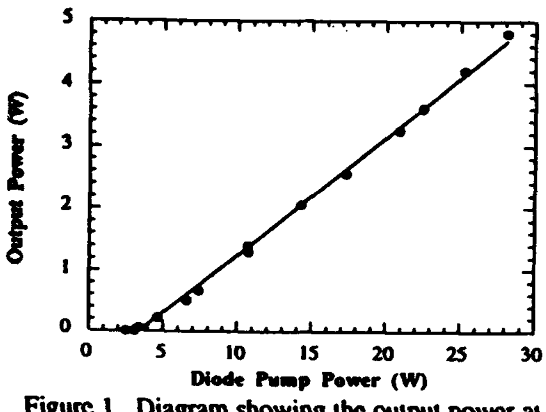

Figure 1. Diagram showing the output power at 1.06 μm vs. diode pump power. The slope efficiency was 19% with a threshold of 3.4 W.

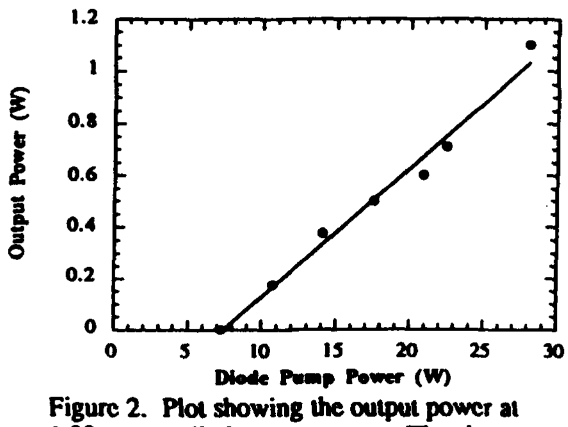

Figure 2. Plot showing the output power at 1.32 μm vs. diode pump power. The slope efficiency was 5% with a threshold of 7.25 W.

A simple near-hemispherical cavity was used in all of the experiments described here. The curved mirror (R = 1 meter) was placed as close as possible to the gain medium while

the flat mirror was located roughly 20 cm away. To characterize the laser performance at 1.06 μm, we measured the output power as a function of input pump power, as shown in figure 1. We obtained a maximum power of 4.8 watts. The threshold power was 3.4 watts and the slope efficiency was 19% with a 4% output coupler. Because of the standing-wave cavity design, the laser operates in several axial modes. Longitudinal-mode beating was observed on an RF spectrum analyzer at the expected TEM_{00} mode spacing. No evidence of transverse-mode beating was observed within the experiment's dynamic range of 40 dB. Because of the Brewster angle slab design, the laser operates in a single polarization with a polarization ratio of greater than 500:1. Using a knife-edge to measure the beam waist, we find an M^2 of 1.07 in the horizontal zig-zag direction and 1.2 in the vertical direction. It is not surprising that the horizontal direction has a lower M^2 value since the zig-zag optical path averages out the thermal distortion. The laser operated in a TEM_{00} mode at all powers.

We also investigated operation of the laser at 1.32 μm by changing the cavity mirrors. The reflectivity of the mirrors were measured on a spectrophotometer. Both mirrors were coated for operation at 1.32 μm and were highly transmissive at 1.06 μm to prevent operation on this higher gain line. We confirmed that the output was indeed at the expected wavelength using an Ando optical multichannel analyzer. The output power versus pump power for the 1.32 μm laser is shown in figure 2. A maximum power of 1.1 watt was obtained. With a 1.3% output coupler, the threshold was 7.25 watts and the slope efficiency was 5%. This is not the optimum output coupling for the laser but we were limited in our choice of optics at 1.32 μm. As before, the 1.32 μm laser operates in a TEM_{00} mode at all powers. This was confirmed by observing the beat note on an InGaAs detector with response out to 1.6 μm.

In conclusion, we have built and operated a 5 watt 1.06 μm and a 1 watt 1.32 μm, cw, TEM_{00} mode, diode-laser pumped, Nd:YAG slab laser. We have developed a low loss, low cost Teflon® AF coating to protect the total internal reflection surfaces of the slab laser, resulting in efficient operation in a side-pumped design. The knowledge we have gained from this lower power laser will be applied to a high power, diode-laser-pumped slab laser with application in gravitational-wave detection, high-conversion-efficiency non-linear optics and coherent communications. We hope to have the high power laser operating within a year.

References:

1. A. Abramovici, W.E. Althouse, R.W.P Drever, Y. Gürsel, S. Kawamura, F. Raab, D Shoemaker, L. Sievers, R.E. Spero, K.S. Thorne, R.E. Voght, R. Weiss, S. Whitcomb and M.E. Zucker, Science, **256**, 325 (1992).
2. Teflon® AF, DuPont product literature (DuPont Polymers, P.O. Box 80711, Wilmington, DE 19880-0711).
3. Spectra Diode Laboratory product information (80 Rose Orchard Way, San Jose, CA 95134-1356).
4. J.M. Eggleston, T.J. Kane, K. Kuhn, J. Unternährer and R.L. Byer, IEEE J. Quantum Electron., **QE-20**, 289 (1984).
5. A.E. Siegman, *Lasers* (University Science, Mill Valley, CA, 1986).
6. Optovac product information (E. Brookfield Rd., N. Brookfield, MA 01535).
7. C. Lüchinger, H. von Arb, F. Studer and J.R. Unternährer, Opt. Engineering, **32**, 786 (1993).
8. Fluorinert® solvents, 3M product information (3M Industrial Chemical Products Division, St. Paul, MN 55144-1000).
9. D. Findlay and R.A. Clay, Phys. Lett., **20**, 277 (1966).
10. A.D. Farinas, Y. Kaneda, E.K. Gustafson and R.L. Byer, CLEO '93, (Optical Society of America, Washington, D.C., 1993) paper CThR2.